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TS Magnetic Field Measurement

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Abstract – I discuss the problem of measuring the TS field. I suggest that the important properties of the installed field can be measured with a combination of limited actual field maps and a measurement of some integral field properties using low energy particle tracking.

Measuring the magnetic field in the TS will be extremely difficult. The cross section of the bore volume is not uniform, it is curved, and it will be difficult to position a measuring device with good precision in the bore. Further, it will be difficult to orient precisely a Hall probe so that small (e.g. ϕ and R) components of the field vector are not contaminated by probe misalignments mixing in a fraction of the major (s) component of the field. This being said, it is worth considering the purpose of the field measurement and what must be known. It is also worth considering alternatives to a complete mapping of the field.

First, what is the purpose of the mapping? One purpose is to check that simple things are right, for example that there are no shorted coils, that a coil is not wired backwards (if that is possible), that the turn count is correct, etc. A second purpose is to have a field map that can be used for Monte Carlo, for example to predict the beam momentum and transverse position distribution at the DS and the pion contamination. For these purposes, maps of individual magnets could be done before final installation when access is easier, probably even when the magnet is warm. Some could be done at the manufacturer. These measurements, probably without the return yokes, could be verified against calculations and used to produce a map for muon beam simulations. They would verify things like ripple, coil tilts, etc.

From the point of view of field quality of the final installation, particularly as it affects transmission efficiency and backgrounds, I argue that only two important characteristics must really be verified. The first is the absence of local field minima in the straight parts of the TS, which could cause particle-traps. These could be caused, for example, by final cold, energized coil placement errors that cause the superimposed fields to develop local minima. To detect such problems, it is sufficient to measure the *s* (axial) component of the field, and only in the straight sections. For the regions near the interfaces with the PS and the TS, this should not be extremely difficult, since access is relatively easy even extending slightly into the curved part. The straight region in the middle of the TS is more problematic. It is probably necessary to remove the collimator and window, and insert a mapping device that can access the full straight section and slightly into the curved section. An issue is how far into the curved section must be measured. There is a field specification on monotonic decrease in field only where dB_s/dR is less than a certain (negative) value, and this specified how far into the curve it is necessary to verify the monotonic decrease. If the gradient is comfortably below zero in the relevant sections and the calculated field comfortably meets the specification, then a very precise measurement is not needed.

An alternative to a full volume, in-situ map in the straight sections might be to install a number of channels on the wall of the warm bore through which a probe can be passed. Probably 4 such channels spaced at 90 degrees around the bore would suffice to ensure that no local minima exist. They would also measure the ripple. A relatively simple tolerance study would demonstrate whether field traps could be missed with this minimal measurement. A set of simulations could also be done to determine the variation of transmission efficiency (also as a function of momentum) with variations in field properties due, for example, to motions of coil placement during cool-down and energizing the coils. This would inform the discussion of whether a full field map is necessary.

The second issue has to do with how far field lines deviate from the initial transverse position with respect to the bore centerline. There is currently no specification for this property, and MECO found that it was essential to have one. Recall that we use curvature drift to move particles vertically so that positive particles and high-energy negative particles are absorbed in the asymmetric central collimator or drifted into the bore wall. If the field lines are not at a constant transverse position as *s* varies, there will be an additional superimposed drift of particles as they follow the field lines. If these additional transverse drifts are too large, particles that should be transmitted will not return to their initial transverse position when they reach the end of the TS, and they may be absorbed somewhere along the TS bore when they run into an obstruction or the wall of the warm bore.

What can cause field lines to move transversely? In a perfect toroid, field lines maintain a constant transverse position in the bore.

1. With a combination of solenoid and toroid fields, lines move transversely by some amount near the transitions.
2. A systematic tilt of the individual coils, which effectively causes a superimposed dipole field if the individual coil tilts are not small and stochastically distributed.
3. Fringe fields from the PS or DS.

MECO tolerance studies showed that the first two causes were not of major concern with rather routine machining and assembly practice. The third cause was found to be significant without care in the design of the partial pole pieces for the PS and DS.

MECO had a field spec (as should mu2e) that field lines not deviate from their initial transverse position with respect to the bore centerline by more than a certain amount. Mu2e (rather than magnet manufacturers) will assume the risk of failing this spec since it is a function of the fields in all three magnets and there is not a spec that can be applied to the individual magnets that will prevent this failure. Verifying that the spec is met requires knowing some integral properties of the field, but does not require knowing all components of the field on a fine grid in the full volume. The relevant scale for a 2 cm off-axis drift is a systematic transverse field component that is a fraction (2cm / 10 m) of the axial field, just the ratio of the transverse drift to the path-length in the TS. Ensuring that such an integrated transverse excursion does not exist by measuring the field on a fine grid requires knowing that probe misalignments are below 1 mrad, not so easy in my experience.

A better way to certify that this spec is met might be to measure directly the deviation of field lines from the starting position. A way to do that is the following. Consider a low energy electron source that can be positioned at well-known xy positions near the entrance of the TS. These electrons will follow field lines to very good approximation. The curvature drift will be very small by virtue of the small radius of the helix (about 1.5 mm for a 1 MeV/c transverse momentum electron in a 2T field). A simple simulation can check this assertion. The integrated deviation of the field line can be measured by simply measuring where these electrons arrive at the end of the TS. The procedure would be to map out the transmission probability vs. transverse starting position. It would probably be useful to measure the positions both at the anti-proton window and at the end of the transport. The measured excursions at both locations could be compared with the calculated excursions to verify the cold energized coil placement.

The measurements would need to be done in vacuum. Hence, a remotely movable stage would be needed to set the source position, and an APD operating in vacuum could be used as the detector. The required level of the vacuum would be determined by simulation. It would probably be advantageous to have two sources, one at the TS entrance and one at the midpoint, and two APD detectors, one at the midpoint and one at the TS exit, to make these measurements efficiently.

I would propose that the technique be simulated. If it shows good results in simulation (as I expect it will), a simple test could be done with an existing magnet. If the simulation and test both work, I would seriously consider not doing a full in-situ map of the TS field.